# Site Index, Height Growth, Normal Yields, and Stocking Levels for Larch in Oregon and Washington

## P.H. Cochran
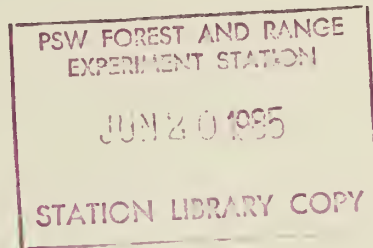
**Abstract**

Even-aged stands of larch in Oregon and Washington have cubic
volume yields similar to yields from larch in Idaho and Montana.
Site index values derived from the heights of the single tallest
tree on 1/5-acre plots at an age at breast height of 50 years
range from 50 to 110 feet.  These values have the same index to
productivity as the site index values of 30 to 90 feet based on
average height of dominant and codominant trees at a total age of
50 years.  Maintaining basal area levels between 45 and 75
percent of normal once trees reach commercial size is
recommended.

Keywords:  Site index, increment (height), yield (forest),
stocking level, larch.

**Introduction**

Western larch (_Larix occidentalis_ Nutt.) is an important
commercial species in the mixed conifer forests east of the
Cascade Range in portions of Oregon and Washington.  Larch occurs
along the east slopes of the Cascades in Washington and north-
central Oregon, in the Ochoco Mountains in Oregon, in the Wallowa
and Blue Mountains of northeastern Oregon and southeastern
Washington, and in the Okanogan Highlands in northeastern
Washington.  Larch is an aggressive pioneer species, existing in
nearly pure, seral stands and also as a component with
Douglas-fir (_Pseudotsuga menziesii_ (Mirb.) Franco), grand fir
(_Abies grandis_ (Dougl. ex D. Don) Lindl.), Engelmann spruce
(_Picea engelmannii_ Parry ex Engelm.), lodgepole pine (_Pinus
contorta_ Dougl. ex Loud.), and ponderosa pine (_Pinus ponderosa_
Dougl. ex Laws.).

P.H. COCHRAN is a soil scientist at the
Silviculture Laboratory, Pacific Northwest
Forest and Range Experiment Station, 1027
N.W. Trenton Avenue, Bend, Oregon 97701.

The most serious pest of larch in the Northwest in recent
years has been the larch casebearer (<u>Coleophora laricella</u>
(Hubner)), an introduced insect. Some native and introduced
parasites now appear to be bringing the casebearer under control.

Larch is easily established and has rapid early growth. With
control of the casebearer likely within the next decade, larch
may be even more important in future managed forests in Oregon
and Washington.

Most of the research on western larch has been conducted in
Montana and Idaho. A summary of much of this research is
available in Technical Bulletin 1520 (Schmidt and others 1976).

This research note presents site index and height growth curves
for even-aged larch stands constructed from data collected in
natural stands in Oregon and Washington. Equations are given for
converting these site index values to those of Bulletin 1520.
Equations describing normal basal area and volume for stands
presented in Bulletin 1520 appear applicable for use in Oregon
and Washington. Tests of this applicability are presented.
Finally, stocking level curves for use in management of even-aged
larch stands are given.

## Site Index and Height Growth Curves

Site index curves are used to indicate the potential productivity
of forest land. The site index curves presented give the esti-
mated height of the tallest tree when the age at breast height of
that tree is 50 years. The height growth curves define the
average pattern of height development for the tallest trees in
stands of a given site quality. Height growth curves are
appropriately used for construction of yield tables but do not
provide optimum estimates of site index from measured height and
age in an existing stand (Curtis and others 1974).

**Construction Method**        The method used is outlined by Cochran (1979b) and is similar to that used by Barrett (1978) and Dahms (1975). The basis of the method was suggested by Curtis and others (1974), and an outline is presented in the appendix.

The age of 50 years at breast height (bh equals 4.5 feet) was chosen as the index age. The site index here is defined as the height of the single tallest tree on a 1/5-acre plot at a bh age of 50 years. Stem analysis data from 18 plots in Oregon and 5 plots in Washington were used to construct the curves.

Some of these plots were sampled in an earlier study (Cochran 1979a, 1979b, 1979c), and they contained Douglas-fir or grand fir. These 1/5-acre plots did have at least one dominant larch which was as tall as or taller than the tallest Douglas-fir or grand fir. Stem analysis showed that these larch had maintained this dominance during the life of the stand. Most of the plots used for constructing curves had at least three dominant larch, and some 1/5-acre plots sampled were pure or nearly pure larch. The characteristics of the plots sampled for construction of site index and height growth curves are given by Cochran (1979b). Briefly, these plots were even aged and had not been disturbed during their history. At the time of sampling, the crown canopy was closed or nearly closed but the closure had only recently occurred. Suppressed trees were absent or nearly so, and competition between trees sufficient to reduce height growth on the dominants was not apparent. The dominant trees did not contain a group of narrow annual rings or show any evidence of top damage. Some plots were rejected after sampling because abrupt breaks in height growth determined from stem analysis showed evidence of past damage even though this damage was not visible at the time of sampling.

Up to five of the tallest larch trees on each plot were felled
and sectioned at a 1-foot stump, at 4.5 feet (bh), at 10 feet,
and then at 10-foot intervals up the stem.  Rings were counted at
each section and were recorded for the appropriate height.
Height was plotted as a function of age at breast height for each
sectioned tree on a single sheet of graph paper for each plot.
All trees for the same plot were graphed together to determine if
the same tree had always been the tallest for its age.  Shifts in
the tree of maximum height with age occur with Douglas-fir and
white or grand fir (Cochran 1979b, 1979c) and also with lodgepole
pine (Dahms 1963), but they occurred with larch on only one
plot.  Freehand curves of height over age at breast height were
drawn for each tree.  The highest points at each decadal age
interval for each plot were used in construction of the site
index and height growth curves.  The site index for each plot was
defined as the tallest height at bh age 50 read from the graph of
heights versus age at breast height for that plot.  Procedures
from this point are given in the appendix.  An understanding of
curve construction leads to an appreciation of their proper use,
so the appendix is recommended reading even for the occasional
user.

**Results**

The distribution of plots by site index was:

| Number of plots | Site index (feet) |
| --- | --- |
| 1 | 48-59 |
| 5 | 60-69 |
| 5 | 70-79 |
| 7 | 80-89 |
| 4 | 90-99 |
| 1 | 100-110 |

The average site index was 78.1 feet.  Because few stands were
sampled beyond a bh age of 100 years, the curves were limited to
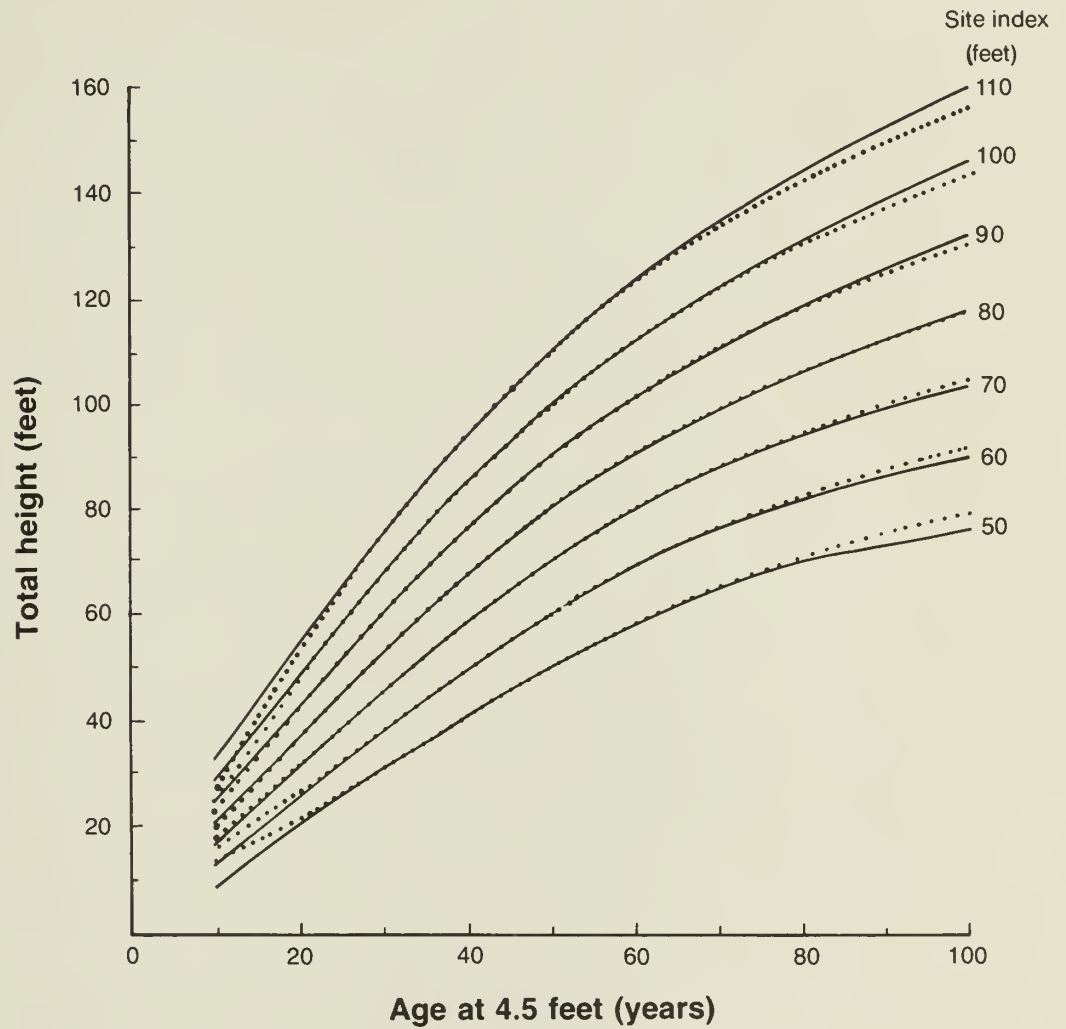bh ages of 100 years or less (fig. 1).

Figure 1.--Site index (solid lines) and
height growth (dotted lines) curves for
western larch.

**Estimating Site Index**     The following procedure is advised for determining the site index of a stand:

A.  Select suitable plots with the following characteristics:

    (1) Even aged at the groundline (practically, there are no remnants from earlier stands and the present stand is one storied).

    (2) No visible signs of past growth suppression or top damage.

B.  Establish boundaries of a 1/5-acre plot with a prespecified shape.

C.  Measure the height of the three tallest trees on the plot.

D.  Extract increment cores from these trees to determine their age at breast height.

E.  Use the breast high age and total height for each tree to determine a site index value for each tree.

    (1) Use figure 1 (the site index curves, not the height growth curves) for rough field estimates.

    (2) Obtain a more precise estimate by using the appropriate a and b values in table 1 to solve the equation,

$$\text{Site index} = 4.5 \text{ feet} + a + b \text{ (height} - 4.5 \text{ feet).} \quad (1)$$

    (3) The appropriate equation in the appendix can be used with a calculator.

Table 1--Values for a and b by years between decades for the family of regressions[1] for estimating site index for western larch

| Age at breast height | 0 | | 1 year | | 2 years | | 3 years | | 4 years | | 5 years | | 6 years | | 7 years | | 8 years | | 9 years | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | a | b | a | b | a | b | a | b | a | b | a | b | a | b | a | b | a | b |
| Years | | | | | | | | | | | | | | | | | | | | |
| 10 | 35.486 | 2.475 | 32.952 | 2.393 | 30.605 | 2.314 | 28.436 | 2.238 | 26.432 | 2.166 | 24.583 | 2.097 | 22.88 | 2.031 | 21.311 | 1.968 | 19.867 | 1.907 | 18.539 | 1.85 |
| 20 | 17.317 | 1.795 | 16.193 | 1.743 | 15.158 | 1.693 | 14.204 | 1.646 | 13.323 | 1.601 | 12.508 | 1.558 | 11.752 | 1.517 | 11.049 | 1.479 | 10.392 | 1.442 | 9.776 | 1.408 |
| 30 | 9.194 | 1.375 | 8.644 | 1.344 | 8.119 | 1.314 | 7.616 | 1.287 | 7.131 | 1.261 | 6.660 | 1.236 | 6.201 | 1.213 | 5.751 | 1.191 | 5.307 | 1.170 | 4.868 | 1.151 |
| 40 | 4.431 | 1.132 | 3.996 | 1.115 | 3.560 | 1.099 | 3.124 | 1.083 | 2.687 | 1.069 | 2.248 | 1.056 | 1.043 | 1.807 | 1.365 | 1.031 | .920 | 1.020 | .475 | 1.010 |
| 50 | 0 | 1.00 | -.417 | .990 | -.862 | .981 | -1.305 | .973 | -1.745 | .965 | -2.181 | .958 | -2.612 | .951 | -3.036 | .949 | -3.452 | .938 | -3.859 | .931 |
| 60 | -4.256 | .925 | -4.641 | .920 | -5.013 | .914 | -5.371 | .909 | -5.713 | .904 | -6.039 | .898 | -6.347 | .893 | -6.637 | .888 | -6.907 | .883 | -7.156 | .878 |
| 70 | -7.384 | .874 | -7.590 | .869 | -7.775 | .864 | -7.936 | .859 | -8.074 | .854 | -8.109 | .849 | -8.282 | .844 | -8.352 | .839 | -8.399 | .834 | -8.425 | .829 |
| 80 | -8.429 | .823 | -8.413 | .818 | -8.377 | .813 | -8.323 | .807 | -8.253 | .802 | -8.167 | .797 | -8.067 | .791 | -7.956 | .786 | -7.836 | .780 | -7.708 | .775 |
| 90 | -7.576 | .770 | -7.441 | .764 | -7.308 | .759 | -7.179 | .754 | -7.057 | .749 | -6.946 | .744 | -6.849 | .740 | -6.772 | .735 | -6.717 | .731 | -6.690 | .727 |
| 100 | -6.695 | .723 | | | | | | | | | | | | | | | | | | |

[1]To estimate site index select the appropriate a and b values for the breast high age of the sample tree. Substitute these values in the equation, Site index - 4.5 feet = a + b (total height - 4.5 feet). For example, for a sample tree 48 years old at breast height and 60 feet in total height, solve the equation S - 4.5 = 0.920 + 1.020 (60 - 4.5), for a site index of 62.0 feet.

F.   Record as the site index value for the plot, the highest of the three values determined.

For plots in even-aged stands with Douglas-fir and grand fir as well as larch, the tallest three to five trees should be sampled regardless of species. The site index for Douglas-fir and grand fir should be determined as described by Cochran (1979b, 1979c). The site index of the plot is the highest site index determined regardless of species. Even though shapes of the curves for the three species are different, there is probably no practical difference in the heights at bh age 50 for the three species on the same site.

Differences in heights of the three species on the same plot at age 50 may be a reflection of slightly uneven ages resulting in slight suppression in height growth of the younger trees or top damage to some species but not to others.

For sites capable of supporting closed crown canopies in Oregon and Washington, site index values for larch as defined here do not range much below 50 feet. When a proper estimating procedure yields a lower site index, past top damage or high stand density has probably reduced height growth. Highest site indexes do not exceed 110 feet for any substantial amount of area.

For the site index curves in Bulletin 1520 (Schmidt and others
1976), an age of 50 years at groundline rather than at breast
height is used. Also, the height in the site index system of
Bulletin 1520 is not the height of the tallest tree on a 1/5-acre
plot but the average height of the dominant and codominant
trees. Age at breast height is easier to determine than age at
groundline. Height of the single tallest tree on a 1/5-acre plot
is easier to determine than the average height of the dominants
and codominants partly because of problems in defining a
codominant. Further, the number of dominant and codominant trees
changes with time. Therefore, site index curves constructed from
stem analysis would not do a good job of predicting a site index
based on a different number of dominants and codominants at ages
younger than the maximum age shown by the curves.

Equations that use age as a variable in Bulletin 1520 use
groundline or total age (A1). For 10 plots of even-aged larch in
Oregon and Washington with site index values (S) ranging from 54
to 100 feet, the age at groundline was determined by digging
around the stumps, cutting the stump at groundline, and counting
the rings for at least five dominant and five codominant trees.
Age at bh (A) was also determined by ring count. The average
number of years necessary to reach 4.5 feet for dominant and
codominant trees is:

$$A1 - A = 13.8 - 0.066 \ (S), \tag{2}$$

$R^2$ is 0.31 and the standard error is 1.7 years.

Bulletin 1520 gives site index values of 30 to 80 feet whereas
Region 1 (Northern Region) Forest Service Handbook (FSH 2409.21g
R1, November 1970, Management of Western Larch--Northern Region)
presents site index values ranging from 30 to 90 feet. If we
assume that the site index values for Region 1 (S1) of 30 to 90

feet are equivalent to the same ranges of heights as the site
index values (S) of 50 to 110 feet as determined for the
Oregon-Washington data, then,

$$S = S1 + 20.\tag{3}$$

So that this assumption could be tested, some summaries of the
original data used to construct the curves presented in Bulletin
1520 were obtained.[1]  These summaries had age at groundline, the
site index S1, and numbers of trees with their average height by
1-inch diameter classes for each plot.  Eighty-six plots were
picked where the height of the tallest larch tree could be
obtained.  For these plots total age ranged from 15 to 114 years,
and S1 ranged from 24 to 84 feet.  Next, S was calculated from
equation (3) and then an age at 4.5 feet was determined from
equation (2) for each plot.  With this age as the age of the
tallest tree, the site index from the appropriate equation in the
appendix was calculated.  This site index, $\hat{S}$, was then related to
the site index, S1, given for the plot.  The result is:

$$\hat{S} = 1.058\ (S1) + 17.93.\tag{4}$$

$R^2$ is 0.81 and the standard error is 7.5 feet.

---

[1] Data furnished by Ward W. McCaughey,
Forester, Forestry Sciences Laboratory,
Intermountain Forest and Range Experiment
Station, Bozeman, Montana 59717, March 3,
1983.

The sum of squares of the difference between S--determined from equation (3)--and $\hat{S}$ ($SS_3$) was calculated for the 86 plots. This sum of squares was used with the sum of squares determined in obtaining equation (4), $SS_4$, to test the joint hypothesis that the slope and intercept are 1 foot and 20 feet, respectively:

$$F = ((SS_3 - SS_4)/2)/(SS_4/84).$$

F with 2 and 84 degrees of freedom was 0.2, and equation (3) was considered valid.

## Normal Basal Areas and Volume Yields

### Methods

To test the validity of equations in Bulletin 1520 (Schmidt and others 1976) for describing normal basal area and volume yields, I assembled 154 observations of the necessary stand data from prism points or plots (at least 1/5-acre in size) taken in stands across the range of larch in Oregon and Washington. Of these 154 samples, 116 were in 32 even-aged larch stands (2 to 16 observations per stand), and the remaining samples were taken in small, scattered pockets of even-aged larch less than 2 acres in size. On all the points or plots at least 60 percent of the basal area was in larch. The site index of each sample was determined by measuring the height and age at breast height of at least the three tallest trees, by calculating the site index for each of these trees from the appropriate equation given in the appendix, and by assigning the highest value obtained as the site index for the sample. Age at breast height was also determined for at least three codominant trees, and the average breast height age of these dominant and codominant trees was used as the breast height age for each sample.

For the plots, the diameter (D) of each tree was measured and at least 15 trees were measured with an optical dendrometer. Total wood volumes inside bark (V) of the trees measured with dendrometers were determined by processing the measurements with the STX program (Grosenbaugh 1964). An equation relating the natural logarithm of volume to the natural logarithm of diameter of the form $\ln V = a + b \ln D + c (\ln D)^2$ was determined for each plot and was used to determine the volume of the remaining trees.

For the prism points, the diameter and height were measured for each counted tree. Equations relating volume (V) to dbh (D), and height (H) were developed from trees sectioned in a previous study (Cochran 1979a):

| Species | Equation | Number of trees | $R^2$ | Standard error |
|---|---|---|---|---|
| Larch | $\ln V = -6.9499 + 1.6782 \ln D + 1.3287 \ln H$ | 133 | 0.994 | 0.096 |
| Douglas-fir | $\ln V = -5.8785 + 1.8357 \ln D + 1.0279 \ln H$ | 210 | .997 | .098 |
| White/grand fir | $\ln V = -6.1860 + 1.7533 \ln D + 1.1684 \ln H$ | 202 | .998 | .096 |
| Engelmann spruce | $\ln V = -5.77345 + 1.8507 \ln D + 1.0182 \ln H$ | 50 | .998 | .083 |
| Western white pine | $\ln V = -6.1498 + 1.7048 \ln D + 1.1769 \ln H$ | 22 | .995 | .087 |
| Ponderosa pine | $\ln V = -6.0336 + 1.8715 \ln D + 1.0166 \ln H$ | 137 | .996 | .109 |
| Lodgepole pine | $\ln V = -5.4821 + 1.9249 \ln D + 0.9139 \ln H$ | 67 | .989 | .120 |

In these equations ln indicates natural logarithms, and V is the cubic-foot volume inside bark including stump and tip calculated by Smalian's formula. The 1-foot stump was assumed to be a cylinder with a diameter equivalent to the diameter at 1 foot inside bark. The number of trees per acre, basal area per acre, volume per acre, and the diameter of the tree of average basal area (Dg) were determined for each sample.

After total age (A1) is converted to age at bh (A), and the site index of Bulletin 1520 (S1) to the site index presented here (S), the equations for estimating normal basal area in square feet per acre and total cubic-foot volume in Bulletin 1520 are:

$$\ln BA = 5.2459 - 25.5667/(A - 0.066S + 13.8)$$
$$+ 0.008543 (S - 20); \tag{5}$$

and

$$\ln V = -7.03317 - 72.1299/(A - 0.066S + 13.8)$$
$$+ 3.07121 \ln (S - 20) + 2.38666 \ln (100 N)$$
$$- 0.36349 (\ln 100 N)(\ln (S - 20)); \tag{6}$$

where:

$$N = \frac{\text{actual basal area}}{\text{normal basal area from equation (5)}}. \tag{7}$$

The above equations were used to calculate the basal area and volume for each of the 154 samples.  Calculated basal areas were compared with actual basal areas.  Calculated volumes were also compared with the volume determined for each plot with the local volume equations or the volume calculated for each point from the equation with ln D and ln H as independent variables.  These volumes determined from local volume equations or from measurements of D and H are referred to here as actual volumes. Site index for these 154 samples ranges from 49.6 to 111 feet. Ages at breast height range from 14 to 146 years and fractions of normal--N, equation (7)--range from 0.38 to 1.81.

**Results and Discussion**     Use of equation (5) resulted in an average overestimate of basal
area of 25.1 percent for the 154 samples. The average absolute
difference between actual and estimated basal areas was 33.8
percent. Percent differences were calculated as actual value
minus estimated value times 100 divided by the actual value.
There was no significant relationship of site index or age with
differences between actual and estimated basal areas. A stepwise
regression relating percent differences between actual and
estimated basal areas to site index and age had an $R^2$ value of
0.014 and an F value of 1.07 with 2 and 151 degrees of freedom.
F equals the regression mean square divided by the residual mean
square in the analysis of variance. The average fraction of
normal for these 154 samples (equation 7) was 0.87.

"Actual" volumes for the 154 samples averaged 4,741 $ft^3$/acre, and
the average of estimated values (equation 6) was 4,500 $ft^3$/acre.
The estimated values averaged 4.3 percent lower than actual
values. The average absolute difference between actual and
estimated values was 11.2 percent. These differences were
related to site index. Stepwise regression shows that the
equation relating percent difference between actual and estimated
volumes to site index had an $R^2$ of 0.087 and an F value of 14.5
with 1 and 152 degrees of freedom. Examination of that data
revealed that the percentage of species other than larch
increased with increasing site index values for the points.

When volumes were calculated by the volume equation for larch for
each tree regardless of species, the volume for the 154 samples
averaged 4,504 $ft^3$/acre, 0.5 percent greater than volumes
estimated by equation 6. The average absolute difference was 9.9
percent. There was no meaningful correlation of these percent
differences with site index, age, or fraction of normal. A
stepwise regression relating these percent differences between
actual and estimated volumes to S, A, and fraction of normal

13

produced an equation with an $R^2$ value of 0.03 and an F value of 1.6 with 3 and 150 degrees of freedom.

The results for estimating basal area indicate that a majority of the samples taken in Oregon and Washington had densities lower than normal by Bulletin 1520 standards. The lack of correlation of the differences between actual and estimated values with site index and age, however, indicates that the equation for normal basal area given in Bulletin 1520 or its modification (equation 5) is acceptable for use in Oregon and Washington. The equation for estimating volume (equation 6) takes density into account, and the average underestimate of volumes with this equation was due to the stem volume equations used in estimating volumes for the points. These equations for the other species produced higher stem volumes for the same diameter at breast height and height than did the larch equation. The small differences between values calculated by the larch stem volume equation and equation (6) indicate that equation (6) is suitable for estimating total cubic volume yield for larch in Oregon and Washington.

## Stocking Level Curves

### Methods and Assumptions

The Forest Service in Region 1 (FSH 2409.21, R1, November 1970, Amendment No. 2) recommends commercial thinning from below, leaving 45 percent of normal basal area. They further recommend allowing the stand develop to 75 percent of normal basal area before the next entry. Within these limits, it is assumed that suppression and mortality related to suppression will be avoided without sacrificing too much of the potential of the site to produce usable wood. This assumption needs verfication through studies of growing stock levels.

Stepwise regressions relating trees per acre (T/A) to diameter of the tree of average basal area (Dg), site index (S), and age at breast height (A) were run so that a relationship between tree size, trees per acre, and basal area per acre for normal stands could be obtained. For the 154 observations the actual number of trees per acre was divided by the fraction of normal (equation 7) to produce the number of trees per acre used. Stepwise regression techniques were also used to determine age at breast height as a function of site index, quadratic mean diameter, and stocking level (N).

**Tentative Results**

Both age and site index as well as quadratic mean diameter are significantly related to the number of trees per acre:

$$\ln (T/A) = 10.001 - 1.7301 \ln Dg. \tag{8}$$

$$\ln (T/A) = 9.1273 - 1.74643 \ln Dg + 0.20978 \ln S. \tag{9}$$

$$\ln (T/A) = 6.73066 - 1.98897 \ln Dg + 0.5556 \ln S + 0.34049 \ln A. \tag{10}$$

The residual mean square and $R^2$ values for equations 8, 9, and 10 are:

| Equation | Residual mean square | $R^2$ |
|----------|----------------------|-------|
| 8 | 0.00887 | 0.983 |
| 9 | .00702 | .986 |
| 10 | .00101 | .998 |

A is related to Dg and S by:

$$\ln A = 7.0389 - 1.01552 \ln S + 0.71232 \ln Dg. \tag{11}$$

$R^2$ is 0.69, and the residual mean square is 0.05188.

Adding the natural log of the stocking level reduced the residual mean square only slightly to 0.05166, so the addition of ln N as an independent variable was not accepted.

From equations (10) and (11), tentative stocking level curves (fig. 2) were created. These curves display the influence of site index as well as quadratic mean diameter on basal area and trees per acre for managed stands of larch of commercial size.

## Summary

Lack of meaningful correlation between differences in measured and predicted values of basal area and larch volume per acre to site index and age at breast height indicate several things: (1) The equations of Bulletin 1520 (Schmidt and others 1976) for estimating normal basal area and cubic volume yield are applicable for larch in Oregon and Washington; (2) for bh ages up to 100 years the site index values as determined in this paper can be converted to the site index values presented in Bulletin 1520 and vice versa; (3) the equation relating total or groundline age to age at breast height is reasonable; and (4) several other tables, equations, and graphs concerning larch volumes and yields in Bulletin 1520 are applicable to Oregon and Washington. When necessary, conversions from total age to age at breast height and from the site index values of Bulletin 1520 to the site index values presented here can be easily accomplished.

## Metric Equivalents

1 acre = 0.405 hectare

1 foot = 0.304 8 meter

1 square foot/acre = 0.229 568 square meter/hectare

1 tree/acre = 2.47 trees/hectare

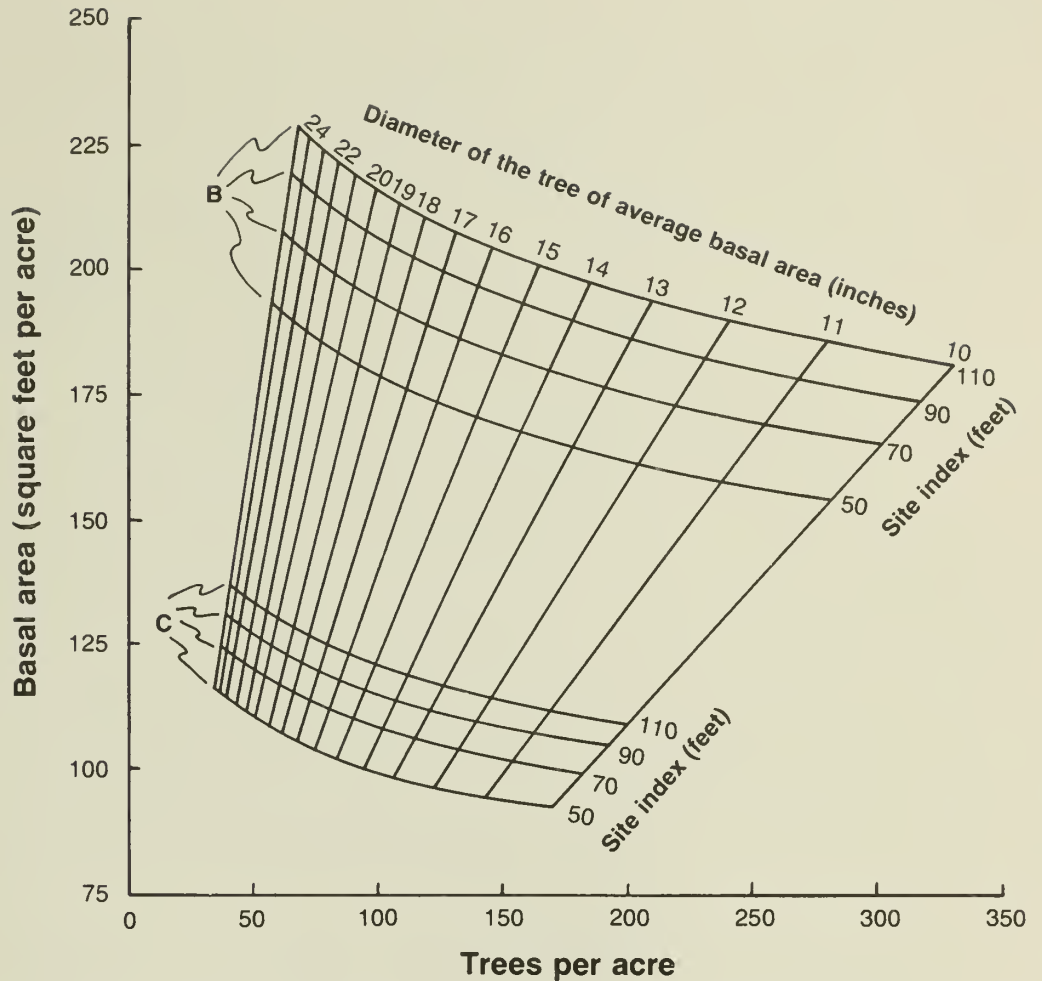1 cubic foot/acre = 0.069 972 cubic meter/hectare

Figure 2.--Stocking level curves for
larch. The "B" lines represent 75
percent of normal stocking, and the "C"
lines represent 45 percent of normal
stocking. Stands should be managed so
that they are at the "B" level for a
commercial entry. Commercial thinnings
should be from below and should reduce
stocking to the "C" level.

**Literature Cited**

Barrett, James W. Height growth and site index curves for managed, even-aged stands of ponderosa pine in the Pacific Northwest. Res. Pap. PNW-232. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1978. 14 p.

Cochran, P.H. Gross yields for even-aged stands of Douglas-fir and white or grand fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-263. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1979a. 17 p.

Cochran, P.H. Site index and height growth curves for managed, even-aged stands of Douglas-fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-251. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1979b. 16 p.

Cochran, P.H. Site index and height growth curves for managed, even-aged stands of white or grand fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-252. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1979c. 13 p.

Curtis, Robert O.; DeMars, Donald J.; Herman, Francis R. Which dependent variable in site index-height-age regressions? Forest Science. 20(1): 74-87; 1974.

Dahms, Walter G. Correction for a possible bias in developing site index curves from sectioned tree data. Journal of Forestry. 61(1): 25-27; 1963.

Dahms, Walter G. Gross yield of central Oregon lodgepole pine. In: Management of lodgepole pine ecosystems symposium proceedings; Baumgartner, David M., ed. Pullman, WA: Washington State University Cooperative Extension Service; 1975: 208-232.

Grosenbaugh, L.R. STX-FORTRAN 4 program for estimates of tree populations from 3P sample-tree-measurements. Res. Pap. PSW-13. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1964. 49 p.

Schmidt, Wyman C.; Shearer, Raymond C.; Roe, Authur L. Ecology and silviculture of western larch forests. Tech. Bull. 1520. Washington, DC: U.S. Department of Agriculture, Forest Service; 1976. 96 p.

Both site index and height growth curves are constructed from an average height curve determined from data from all the plots and then adjusted to the desired site index by use of the linear relationship existing between height and site index at any age. Height growth and site index curves are different because the equations

$$S - 4.5 \text{ feet} = a + b \ (H - 4.5 \text{ feet}) \text{ and}$$

$$H - 4.5 \text{ feet} = a_1 + b_1 \ (S - 4.5 \text{ feet})$$

have different slope and intercept values for all ages except the index age.

**Site Index Curve Construction**

1.  The tallest heights (H) at each decade were read from the freehand curves and related to the site index S for each plot by the equation $S - 4.5 \text{ feet} = a + b \ (H - 4.5 \text{ feet})$. The following estimates were obtained:

| Age at breast height (Years) | a | b | $R^2$ | Standard error of the estimate | Number of observations |
|---|---|---|---|---|---|
| 10 | 34.9375 | 2.4723 | 0.66 | 7.54 | 23 |
| 20 | 17.1072 | 1.8104 | .81 | 5.66 | 23 |
| 30 | 11.0280 | 1.3345 | .93 | 3.35 | 23 |
| 40 | 2.7235 | 1.1636 | .98 | 1.6 | 23 |
| 50 | 0 | 1.0 | 1.0 | 0 | 23 |
| 60 | -2.8567 | .9091 | .98 | 1.78 | 23 |
| 70 | -8.0847 | .8777 | .96 | 2.58 | 23 |
| 80 | -8.9310 | .8184 | .95 | 2.91 | 18 |
| 90 | -12.0663 | .7821 | .94 | 3.08 | 11 |
| 100 | -9.9663 | .7215 | .92 | 3.77 | 9 |

The nine sample plots at bh age 100 have site indexes of 48.6, 62, 70, 78, 78, 82, 83, 86.8, and 87.4 feet.

2. The above decadal estimates of b were smoothed over age at breast height (A) (fig. 3) by the equation (forced through the b value of 1 at a breast high age of 50 years),

$$\hat{b} = 3.51412 - 0.125483A + 0.0023559A^2 - 0.00002028A^3 + 0.000000064782A^4.$$
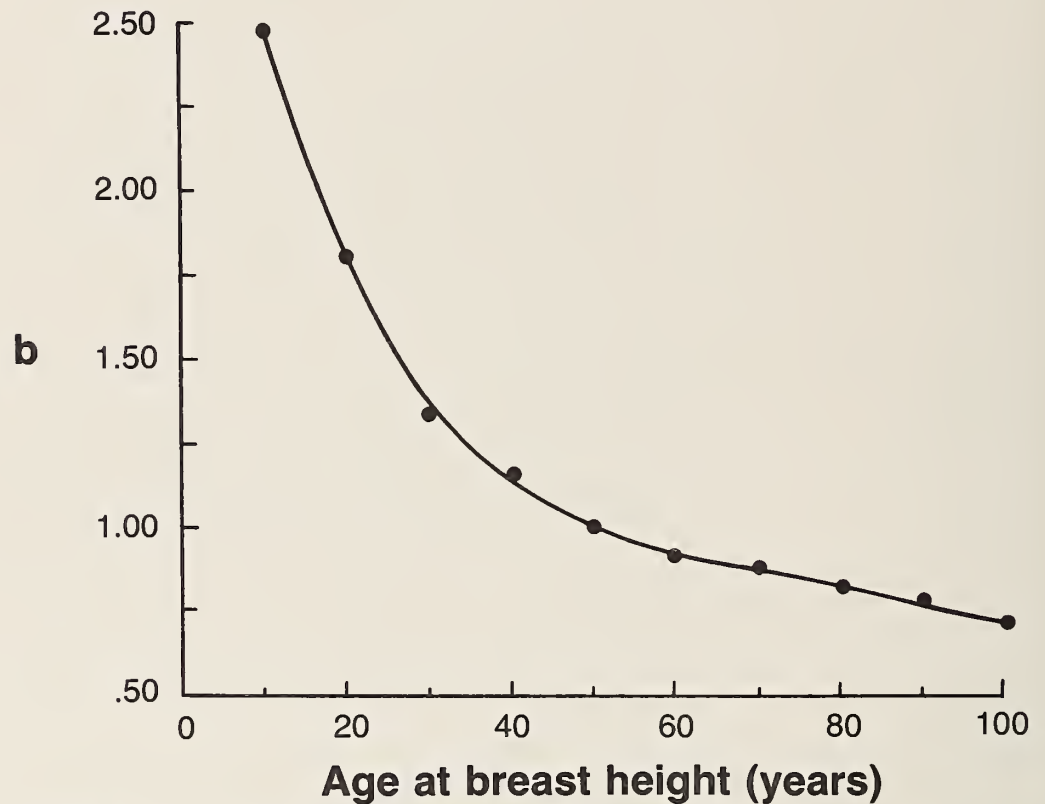


Figure 3.--b values as a function of age in the equation, S - 4.5 feet = a + b (H - 4.5 feet). Points are actual b values. Solid line is the curve expressed by the equation,

$$\hat{b} = 3.51412 - 0.125483A + 0.0023559A^2 - 0.00002028A^3 + 0.000000064782A^4.$$

The standard error and $R^2$ values for this equation are 0.0183 foot and 0.9989. The resulting $\hat{b}$ values are those appearing in table 1.

3.  The following equation (with a standard error of 0.11 foot
    and an $R^2$ of 0.999), expressing decadal mean heights ($\overline{H}$) as
    a function of age, was forced through the mean site index
    (78.07 feet) at 50 years and a height of 4.5 feet at 0 years
    (fig. 4):

$$\hat{H} - 4.5 \text{ feet} = 1.46897A + 0.0092466A^2 - 0.00023957A^3 + 0.0000011122A^4.$$

Here $\hat{H}$ is an estimate of $\overline{H}$. At ages beyond 70 years, the sample
became progressively smaller an the mean site was slightly
different.  Average heights were adjusted to the mean overall
site index using $a_1$ and $b_1$ values of the individual
regression  of $H - 4.5 \text{ feet} = a_1 + b_1 (S - 4.5)$ with $S$
equaling 78.07 for ages 80, 90, and 100 years before fitting the
average height curve.

4.  H and the smoothed slope b of regressions for each year were
    then used to calculate the corresponding intercept a:

$$\hat{a} = \overline{S} - 4.5 - \hat{b} \, (\hat{H} - 4.5).$$

These "a" values appear in table 1.

5.  Substituting expressions for a, b, and H in the linear
    equation of step 1 gives the final equation used to estimate
    site index as a function of breast high age and height
    (fig. 1).

$$S = 78.07 + (H - 4.5) (3.51412 - 0.125483A + 0.0023559A^2 - 0.00002028A^3 + 0.000000064782A^4) - (3.51412 - 0.125483A + 0.0023559A^2 - 0.00002028A^3 + 0.000000064782A^4) (1.46897A + 0.0092466A^2 - 0.00023957A^3 + 0.0000011122A^4).$$
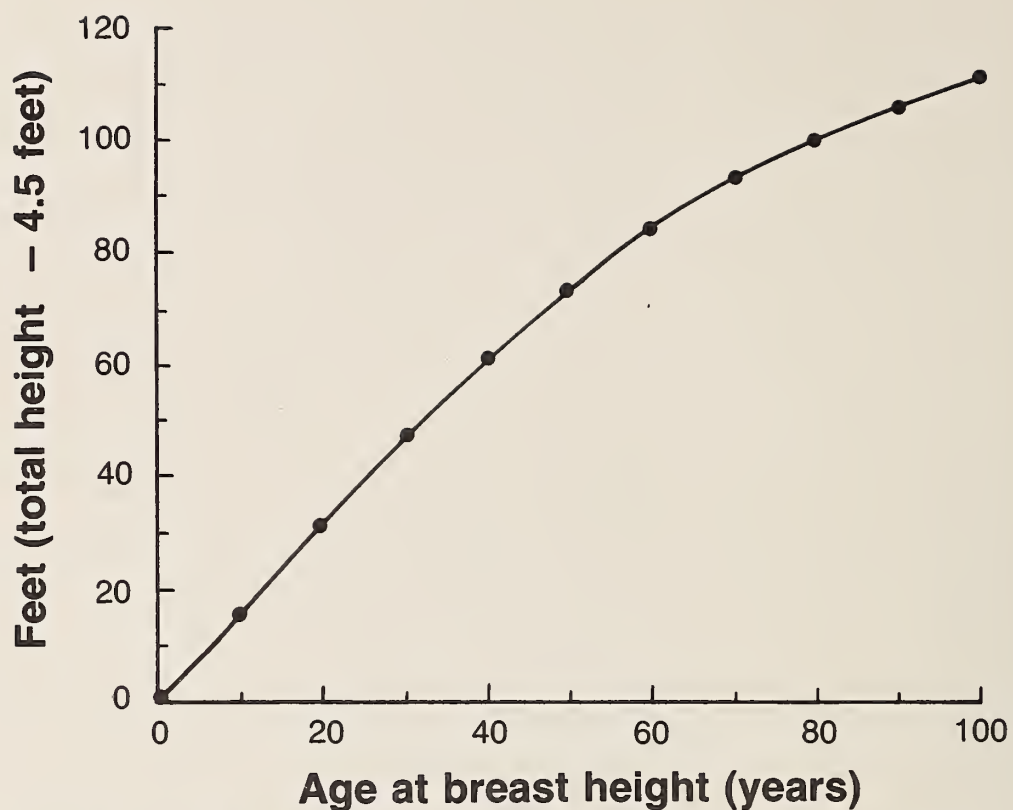
Figure 4.--Average of the tallest heights
for each decade minus 4.5 feet for the
plots used in construction of the site
index and height growth curves. Points
are actual values minus 4.5 feet. The
solid line is expressed by the equation,

$$\overline{H} - 4.5 \text{ feet} = 1.46897A + 0.0092466A^2$$
$$- 0.00023957A^3$$
$$+ 0.0000011122A^4.$$

Height in this equation is considered to
be the average height of the tallest trees
for the sampled plots as a function of age
at breast height.

1.  The site indexes for each plot were related to the tallest
    heights at each decade by the equation:

$$H - 4.5 = a_1 + b_1 (S - 4.5);$$

and the following estimates were obtained:

| Age at breast height | $a_1$ | $b_1$ | $R^2$ | Standard error of the estimate | Number of observations |
|---|---|---|---|---|---|
| (Years) | | | | | |
| 10 | -4.1042 | 0.2682 | 0.66 | 2.48 | 23 |
| 20 | -1.7242 | .4473 | .81 | 2.81 | 23 |
| 30 | -4.5870 | .6994 | .93 | 2.43 | 23 |
| 40 | 1.3808 | .8464 | .98 | 1.36 | 23 |
| 50 | 0 | 1.0 | 1.0 | 0 | 23 |
| 60 | 4.6559 | 1.0794 | .98 | 1.94 | 23 |
| 70 | 12.5292 | 1.0942 | .96 | 2.89 | 23 |
| 80 | 15.6530 | 1.1563 | .95 | 3.46 | 18 |
| 90 | 20.8149 | 1.2022 | .94 | 3.82 | 11 |
| 100 | 21.2321 | 1.281 | .92 | 5.03 | 9 |

2.  The above decadal estimates of $b_1$ were smoothed over age
    (fig. 5) by the equation:

$$\hat{b}_1 = -0.12528 + 0.039636A - 0.0004278A^2 + 0.0000017039A^3.$$

The standard error and $R^2$ values are 0.017 foot and 0.9909.

3.  Appropriate rearrangement and substitution for $a_1$, $b_1$,
    and H in the linear equation of step 1 gives the final
    equation used to estimate height as a function of age and
    site index:

$$\begin{aligned}
H = {} & 4.5 + 1.46897A + 0.0092466A^2 - 0.00023957A^3 \\
& + 0.0000011122A^4 + (S - 4.5)(-0.12528 + 0.039636A \\
& - 0.0004278A^2 + 0.0000017039A^3) - (73.57)(-0.12528 \\
& + 0.039636A - 0.0004278A^2 + 0.0000017039A^3).
\end{aligned}$$

Figure 5.--$b_1$ values in the equation
H - 4.5 feet = $a_1$ + $b_1$ (S - 4.5 feet) as
a function of age.   Points are actual $b_1$
values.   The solid line is expressed by
the equation,

$$\hat{b}_1 = -0.12528 + 0.039636A - 0.0004278A^2 + 0.0000017039A^3.$$